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SWORDS TO PLOWSHARES

A Short History of Oak Ridge National Laboratory

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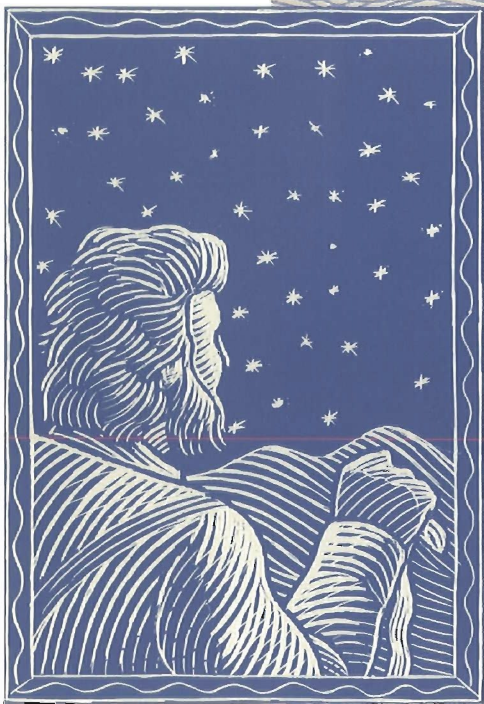
FIRST, A VISION

A half century after the fact, even those who were there—a part of the events—have irretrievably lost details, nuances, even the dreadful intensity of the experience; those who weren't there cannot begin to grasp the fear and urgency in all their enormity. ¶ To say that war raged across much of the world would be coldly abstract; to say that millions had died and millions more were yet to die is nearly as abstract, leaving out as it does the real suffering of real people. ¶ Amid all the pain and fear came an even darker omen, one known only to a relative handful of people: physicists knowledgeable enough to see the implications of the discovery of uranium fission in 1939 by two German scientists. The fissioning, or splitting, of uranium's nucleus could unleash energy of unprecedented might and destructiveness, these physicists realized, if it could be harnessed for a bomb. Scientifically, Germany had a head start; pragmatically, with the 1940 conquest of Belgium, Hitler appeared poised to tap the abundant uranium ore of the Belgian Congo. ¶ But first things must come first. To understand the story of Oak Ridge fully—that is to say, to grasp not just the facts but also the deeper truths and symbols—you must first know the story of John Hendrix, a mystic who roamed the East Tennessee woods around the turn of the century, more than 40 years before Oak Ridge existed. ¶ One day, after weeks of absence, Hendrix reappeared at a crossroads store and told a group of neighbors he'd seen a startling vision. ¶ "In the woods, as I lay on the ground and looked up into the sky, there came to me a voice as loud and as sharp as thunder," Hendrix reported. "The voice told me to sleep with my head on the ground for 40 nights and I would be shown visions of what the future holds for this land.... And I tell you, Bear Creek Valley someday will be filled with great buildings and factories, and they will help toward winning the greatest war that ever will be. And there will be a city on Black Oak Ridge.... Big engines will dig big ditches, and thousands of people will be running to and fro. They will be building things, and there will be great noise and confusion and the earth will shake." ¶ "I've seen it," he concluded. "It's coming." ¶ And so it was.



THE FORTIES

War and Peace

It was the best of times and the worst of times: *It's a Wonderful Life* and six million Jewish deaths. "White Christmas" and black lists. Gas rationing and Guadalcanal. *Casablanca* and Hiroshima. V-2 rockets and V-J Day.

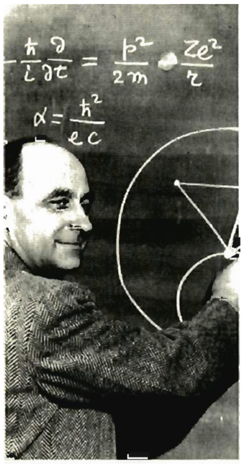
News of the German discovery of fission had reached America within weeks, relayed by Danish physicist Niels Bohr. In July 1939, at the urging of physicists Eugene Wigner and Leo Szilard, Albert Einstein wrote a letter to President Franklin D. Roosevelt urging a U.S. research program. "Einstein understood it in half a minute," recalled Wigner, who was to play a central role in ORNL's early history. "It was really uncanny how he dictated a letter in German with enormous readiness.... I translated that into English.... This helped greatly in initiating the uranium project."

For the next two years, progress was agonizingly slow. Then, in a phenomenon somewhat akin to uranium reaching "critical mass"—the level of concentrated fission necessary to trigger a self-sustaining chain reaction—the Manhattan Project became an urgent national priority. In May 1941, 40 tons of graphite and eight tons of uranium oxide were ordered for experiments. They were to be stacked into atomic "piles," the experimental forerunners to nuclear reactors, made by piling up uranium chunks surrounded by graphite. Graphite, a form of carbon, helped boost the likelihood of fission by slowing neutrons, particles given off spontaneously by some atoms, and turning them into subatomic "cueballs" that could break apart other atoms.

On December 2, 1942, in a squash court beneath the University of Chicago's Stagg Field, a group of researchers led by Enrico Fermi achieved the world's first self-sustaining fission reaction. "It was as though we had discovered fire," one of the scientists said years later.

To build on the success, massive research and production efforts were parceled out around the country. Led by Fermi and other scientists from Chicago's Metallurgical Laboratory, teams of scientists and engineers undertook secret tasks at a handful of closely guarded sites: a former boys' school on a remote mesa at Los Alamos, New Mexico, the center of weapons design; the experimental cyclotron and labs of the University of California, where physicists explored the properties and explosive potential of a newly created element, later named plutonium; the stark, remote valley of the upper Columbia River at Hanford, Washington, where many pounds of plutonium were to be produced by three massive reactors; and a series of valleys in East Tennessee—isolated but convenient to two rail lines, a river, and the abundant electricity of the Tennessee Valley Authority—where techniques would be devised to produce and purify the large quantities of fissionable uranium and plutonium that would be needed.

Physicist Enrico Fermi, who designed the world's first nuclear reactor (at the University of Chicago), was in Oak Ridge when the Graphite Reactor "went critical" on Nov. 4, 1943.



Wartime Mission Ground was broken for "Clinton Laboratories," as Oak Ridge National Laboratory was called then, on February 2, 1943. By summer, some 3,000 construction workers erected about 150 buildings. The materials list included 30,000 cubic yards of concrete, 4 million board feet of lumber, 4,500 gallons of paint, and 1,716 kegs of nails. Within the boom town of Oak Ridge itself, a house—sometimes loosely defined—was being completed every 30 minutes. The bus system in the secret city would be the nation's sixth largest; electricity consumption (largely because of the gargantuan uranium-enrichment plants called Y-12 and K-25) would be 20 percent greater than New York City's.

The heart of the X-10 site, as the Laboratory was often called, was an experimental reactor far larger and more advanced than Fermi's Chicago pile: a graphite cube 24 feet on each side, with seven-foot-thick concrete walls for radiation shielding. The reactor was riddled with 1,248 channels for air cooling and uranium fueling; the fuel—60,000 cylindrical "slugs" of uranium—was canned, literally, by the Aluminum Company of America. Some of the neutrons freed by the fission chain reaction would be captured by uranium atoms; those atoms would thus be transformed into plutonium, which chemical engineers would figure out how to extract and purify. Besides supplying badly needed experimental quantities of plutonium to the California researchers, the Graphite Reactor and its chemical-separation labs served as pilot-scale models for Hanford's production plants.

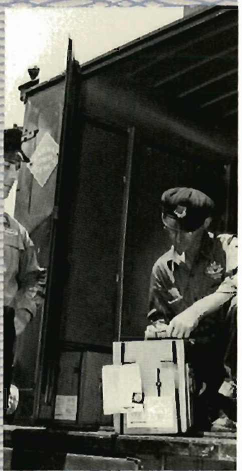
The reactor took just nine urgent months to build. In the predawn hours of November 4, 1943, the reactor "went critical" with a self-sustaining fission reaction—the world's second reactor to achieve one. Over the next year, the reactor performed flawlessly, irradiating thousands of fuel slugs, which were dissassembled and dissolved so the plutonium could be extracted, bit by precious bit. In March 1944, the first plutonium sample big enough to see—sealed in a 5-milliliter test tube—was destined for Chicago but later doomed:

The Graphite Reactor—controlled from this console—irradiated uranium slugs, from which wartime chemists extracted the world's first grams of plutonium.

spilled by a scientist who'd had no sleep for 36 hours. Gradually, though, other shipments met the research needs of Manhattan Project physicists and chemists. By the end of 1944, with Hanford beginning to churn out plutonium, the Graphite Reactor's most urgent mission had been completed and its focus shifted to radioisotope production.

When a uranium-fueled atomic bomb devastated Hiroshima on August 6, 1945, it was powered by the output of Oak Ridge's Y-12 and K-25 plants. Three days later, when a plutonium-fueled bomb struck Nagasaki, the destruction was wrought by Hanford's plutonium—based on Clinton Laboratories' radiochemical groundwork.

Federal express, Oak Ridge-style: In 1946, ORNL became the world's foremost source of radioisotopes for medicine, agriculture, industry, and other uses. This isotope shipment—the 1,000th—took place in July 1947.



Identity Crisis After the war, uncertainty reigned in Oak Ridge. Many workers felt proud that the bombs had helped hasten the war's end. But as pictures of devastation emerged from Hiroshima and Nagasaki, others harbored deep misgivings about the use of the bombs. Through the newly formed Federation of Atomic Scientists, Oak Ridge scientists and colleagues from other Manhattan Project laboratories lobbied Congress for control of atomic power to be shifted into civilian hands. Their efforts helped shape the Atomic Energy Act of 1946, which created the Atomic Energy Commission and gave it jurisdiction over the newly released atomic genie.

But the AEC's creation raised as many troubling questions as it answered for the 1,000 employees of the postwar laboratory. During the war, the Lab's operations had been overseen by DuPont and the University of Chicago; afterward, the government recruited Monsanto to take over. By 1947, though, Monsanto decided to withdraw from its contract. The University of Chicago, which initially agreed to return after Monsanto's withdrawal, later backed out as well.

Even more unsettling than the question of who would oversee the Lab's postwar work, though, was the question of what work would remain to be overseen. "During those days immediately after the war, everything seemed ambiguous," according to Alvin Weinberg, who became the Laboratory's research director, then its director for many years: "the role of nuclear power, the relative priority to be given to reactors for power and reactors for military propulsion, the role of basic nuclear research, the responsibility of the Laboratory to the scientific educational community of the Southeast. Then there were many practical questions: Who would operate the Laboratory, who would be its permanent director; indeed, would the Laboratory survive?"

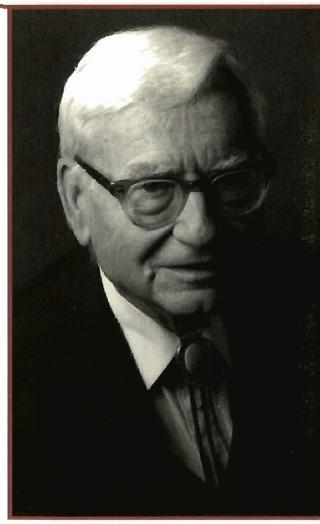
After months of uncertainty, Union Carbide and Carbon Co. (later Union Carbide Corp.), which already operated Oak Ridge's two other AEC installations, agreed in December 1947 to manage the Lab—a job it would hold until 1984. But that same December—a season dubbed "Black Christmas" in Oak Ridge—the AEC sharply curtailed Oak Ridge's plans for leading the development of nuclear power. The Materials Testing Reactor, a powerful new research reactor ORNL was designing for itself, would be built in Idaho, not Tennessee, the AEC decreed. What's more, the leading role in reactor development would be played by Argonne National Laboratory, a new lab built near Chicago on the scientific foundations of the Metallurgical Laboratory. Oak Ridge would be relegated, it seemed, to continuing its isotope production and radiochemical separations—a mission that seemed, in some ways, like a giant step back.

Many workers felt proud that the bombs had helped hasten the war's end. Others harbored deep misgivings.

Postwar Plowshares One unquestioned success during an otherwise uncertain period was the outpouring of radioisotopes—radioactive versions of elements—from the Graphite Reactor to research labs and medical centers throughout the nation. The first shipment beyond the fences of the Manhattan Project was a small quantity of carbon-14, given to a St. Louis cancer hospital in August 1946, two months after *Science* magazine published a "catalog" of Oak Ridge isotopes. During the next 12 months, the Lab made more than a thousand shipments from an inventory of more than 60 different isotopes; by 1950, the number of shipments was nearing 20,000. Looking back in 1976 with the perspective granted by three decades, longtime ORNL director Weinberg wrote, "If at some time a heavenly angel should ask what the Laboratory in the hills of East Tennessee did to enlarge man's life and make it better, I daresay the production of radioisotopes for scientific research and medical treatment will surely rate as a candidate for the very first place."

By the end of the decade, the outlook in Oak Ridge had brightened considerably. The Graphite Reactor was the world's leading source of intriguing and useful new isotopes, as well as a research tool whose capabilities, in the form of neutrons to probe materials, would open a whole new field of science. ORNL's bread-and-butter program, chemical separations, would begin development of new extraction processes that would be adopted by nuclear research and production facilities around the world. The Laboratory embarked on a program of biological research that would earn it global prominence over the coming decades. And with backing from both the U.S. Navy and the Air Force, ORNL edged its way back into reactor development, where it would focus much of its energy for the next decade.

Alvin Weinberg began his career as a biophysicist but turned nuclear physicist for the Manhattan Project. Ever since, he has pondered the complex issues raised by nuclear weapons.



SCIENTISTS AND SECOND THOUGHTS

Despite the urgency driving Manhattan Project work in Oak Ridge and elsewhere, some scientists grew concerned about the atomic bomb, recalls longtime Laboratory director Alvin Weinberg. By July 1945, with Hitler defeated and the first bombs taking shape, dozens of scientists petitioned President Truman to reconsider the weapon.

Leading the petition drive was Chicago physicist Leo Szilard, who had helped initiate the bomb project. In early July, Szilard sent a draft petition to Oak Ridge for signatures; it urged Truman "to rule that the United States shall not, in the present phase of the war, resort to the use of atomic bombs." Eighteen Oak Ridge physicists, including Weinberg, agreed with the petition "in essence," supporting use of the bomb only if Japan ignored warnings about "a new weapon"—and if responsibility for the bombing were shared by America's allies.

Another petition, originating in Oak Ridge, received wider local circulation and more signatures, says Weinberg. This petition maintained that the bomb "should be adequately described and demonstrated, and the Japanese nation should be given the opportunity to consider the consequences of further refusal to surrender."

By mid-July Szilard revised his petition, softening its language before mailing it to Truman with 70 signatures. However, the president never saw Szilard's petition or either of the two from Oak Ridge.

Eventually the scientists would win more of a hearing than they got during the war: After vigorous lobbying by scientists, the Atomic Energy Act of 1946 took authority over atomic weapons away from soldiers and gave it to civilians. In the Cold War decades to come, that sometimes seemed a dubious victory.

Weinberg, who continued to ponder the bomb's use, gradually evolved a stance he calls "the sanctification of Hiroshima."

"In recent years, I've argued that dropping the bomb was the proper thing to do," he explains, "because it was the only way to impress on humanity the terrible nature of nuclear weapons. We have to invest them with the force of religious taboos, which are the only things strong enough to last for millennia." He adds, "The images of Hiroshima have that force.

"It's the only way to keep nuclear weapons from ever being used again."

THE FIFTIES

Glory Days

Korea and Kruschev. I Like Ike, but *Gentlemen Prefer Blondes*. The Red Scare and "Blue Suede Shoes." Peter Pan and the Kinsey Report. June Cleaver and Joseph McCarthy. Edsel and Sputnik. Hula hoops and H-bombs.

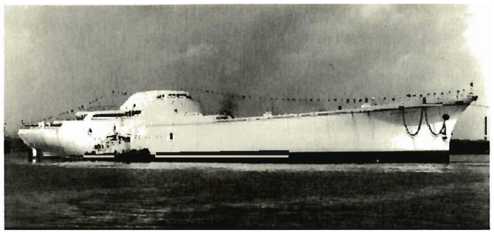
After the feverish pitch of the Manhattan Project subsided and the AEC resolved the postwar, Hamlet-like question it had raised for ORNL—"to be or not to be"—the Laboratory settled in for the scientific long haul. By the time President Dwight D. Eisenhower made his historic "Atoms for Peace" speech to the United Nations in 1954, work was already beginning on America's first commercial nuclear power plant (the first step toward electricity "too cheap to meter"), and ORNL had long since hitched its scientific wagon to a constellation of nuclear stars: Fission for propulsion and electricity. Radioactive and stable isotopes for university science, industrial applications, and cancer research and treatment. New ways to separate and purify the exotic chemicals of the atomic age. The brave new physical and chemical worlds discovered during work on the bomb.

Atoms for Power The fifties were the glory days of fission reactor development at ORNL. More nuclear reactors were built or designed at the Laboratory during this decade than in all other decades combined: The Low Intensity Test Reactor. The Homogeneous Reactor (1 and 2). The Bulk Shielding Reactor. The Aircraft Reactor Experiment. The Tower Shielding Reactor. The Molten Salt Reactor. The Oak Ridge Research Reactor. The Geneva Conference reactor. The Package Power Reactor. The Experimental Gas-Cooled Reactor.

At this distance their names sound sterile, academic, but at the time they were a litany of hope and promise, of people's life work, and—in some cases—of dreams deferred or dashed outright.

Ironically, despite the lofty ideals behind the Atoms for Peace motto, it was the Cold War and the U.S. military that subsidized much of ORNL's reactor development during the 1950s. In the race to harness controlled fission, the Navy got out of the gate first, thanks largely to Captain Hyman Rickover, who spent a year learning reactor technology in Oak Ridge after World War II and went on to develop a fleet of nuclear-powered submarines and surface ships. But the Air Force made a determined bid to build its own nuclear fleet, of long-range bombers. And while the plane itself never got off the ground, it did launch three experimental ORNL reactors and a host of related work. It also subsidized the Laboratory's first particle accelerators, which long outlasted the airplane project, and its first computers, which were used for complex radiation and shielding calculations. ORNL's first computer was also the South's first computer; the Lab's second, a vacuum-tube machine called ORACLE, was for a time the world's finest computer—possessing a fraction of the speed and power of today's desktop machines.

The futuristic *Savannah*, the nation's first (and only) nuclear-powered civilian ship, hoisted its atomic anchor in 1959. ORNL scientists made sure the vessel's reactor shielding was shipshape.

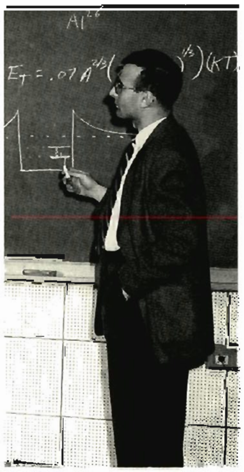


Other, earthbound reactor programs fared better than the ill-fated plane.

For the U.S. Army, ORNL designed a transportable reactor to generate heat and electricity for remote military bases. Its modular fuel core, designed for easy replacement every two years, was smaller than a garbage can but generated as much power as 54,000 barrels of diesel fuel. The first of the "package" reactors, built in the mid-1950s by American Locomotive Co., was installed at Fort Belvoir, Va., to train operators; eventually a handful of the compact, modular units were built and flown to bases in such out-of-the-way places as Greenland, the Panama Canal Zone, and Antarctica.

In terms of public prominence and column inches, at least, the ORNL reactor with the greatest impact in the 1950s was a small "swimming-pool" reactor—one with a square, open tank of cooling water—shipped to Geneva, Switzerland, in 1955 for the first United Nations Conference on Peaceful Uses of the Atom. A sort of international science fair marked by Cold War competitive zeal, the conference was the first global showcase for the peacetime possibilities of nuclear energy. Although the Geneva reactor was small—a one-thirtieth scale model of the Materials Testing Reactor ORNL had hoped to build in the late 1940s—it stole the Geneva spotlight. After the conference, the nomadic reactor was sold and shipped to a research institute in Switzerland.

As the Cold War intensified in the early '50s, physicist Alex Zucker helped resolve a nightmarish concern by deducing that a hydrogen-bomb explosion could not ignite the atmosphere.



Two ORNL reactor programs in the 1950s were ambitious (but ultimately unsuccessful) bids to redirect the course of civilian nuclear power. In 1952 the Lab built a small (1-megawatt) "homogeneous" reactor, one in which a liquid uranium solution was used both as fuel and as the source of steam to spin a generator's turbine. Besides offering potentially higher generating efficiencies than solid-fuel designs, it offered an important operational advantage: Its fuel solution could be routed continuously through a processing plant for purification and replenishment so the reactor would not require shutdowns for refueling. In 1957 ORNL built a larger homogeneous reactor, one modified to irradiate thorium and "breed" uranium while it generated power. But by then work on a solid-fuel breeder was well under way, and the AEC soon abandoned the liquid-fuel alternative.

Undeterred, ORNL was soon exploring another new design, one that had recently been built in Britain: a reactor whose uranium-oxide fuel was cooled by a gas (helium) rather than a liquid. The

The genes of mice and men are remarkably similar, a kinship that ORNL geneticist Liane Russell (shown here in 1950) used in researching radiation effects and discovering the gender-determining function of the Y chromosome.

AEC began building a large test reactor in Oak Ridge in 1959, but the project was plagued by delays, cost overruns, and dwindling technical relevance. The project was finally killed by the AEC in 1964, but not before its glistening silver containment dome had been erected: a monument to—or perhaps a forewarning of—the uncertainties looming over nuclear R&D and nuclear power.

Ultimately, ORNL's greatest impact on nuclear power during the 1950s came not from reactor design but reactor training: In 1950, at the AEC's request, the Laboratory established the Oak Ridge School of Reactor Technology to share nuclear know-how with visiting personnel from universities, industry, and the military. Over the next decade and a half, the school's one-year curriculum would train nearly 1,000 graduates, including many of the pioneers of commercial nuclear power.

Wishing Upon a Star In the late fifties, a new nuclear technology emerged as the hope for the energy future: thermonuclear fusion, the reaction that powers both the hydrogen bomb and the stars. Fueled by a hydrogen isotope found in ordinary water, fusion promised clean energy until the oceans ran dry. Fusion quickly became the holy grail of boundless energy.

By 1958, when the UN held its second conference on peaceful uses of the atom, fusion was taking the spotlight from fission. In a rush of optimism that would prove many decades premature, the AEC urged the Laboratory to demonstrate controlled fusion in time for the conference. Gamely, the Lab sent two fusion devices, which featured an actual fuel plasma consisting of magnetically confined ions—charged atoms—of the hydrogen isotope deuterium. In the years and decades to come, fusion, like fission, would prove far more challenging than at first glance.

In the end, perhaps the most successful product of ORNL's 1950s reactor-building spree was the most purely science-oriented one: the Oak Ridge Research Reactor, a 20-megawatt (later boosted to 30) "swimming-pool" reactor offering the nation's second-highest neutron flux. (The materials reactor ORNL had lost to Idaho offered higher neutron flux but far less experimental flexibility.) Completed in 1958, the reactor served for the next 30 years as a workhorse for studying the effects of radiation, probing the structure of materials, and turning out a steady supply of isotopes.

Recycling Reactor Fuel Throughout the fifties, ORNL built strongly on its wartime foundation of synthesizing and extracting plutonium. Spent fuel and other wastes from the mammoth plutonium-production reactors at Hanford contained valuable quantities of uranium and plutonium, and in the early years of the decade, ORNL refined a solvent extraction process called REDOX to mine the wastes for these precious commodities. The Lab devised a similar process to recover uranium from used fuel plates at the Materials Testing Reactor in Idaho and helped develop two other widely used extraction processes, PUREX (for plutonium and uranium extraction at the AEC's Savannah River and Hanford sites) and THOREX (for extracting thorium and the weapons isotope uranium-233). This work became the foundation for nuclear-fuel processing around the world.

Fueled by a hydrogen isotope found in ordinary seawater, fusion promised clean energy until the oceans ran dry.

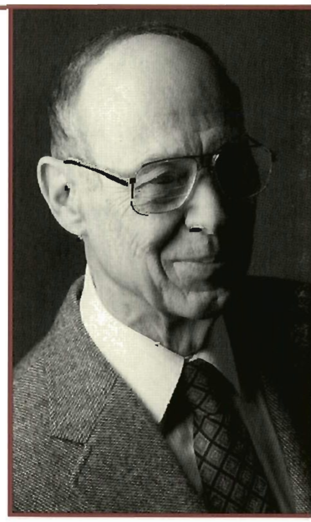
By mid-decade, when nuclear energy "too cheap to meter" promised to create an insatiable hunger for fuel, ORNL was planning a massive plant to reprocess the nation's supply of spent reactor fuel and extract the uranium, thorium, and plutonium. The early nuclear-age recycling plant never got built; the AEC figured it would compete unfairly with similar, commercial facilities—facilities that likewise fell by the nuclear wayside.

Atoms for Health In sharp contrast to the fluctuating fortunes of reactor development, ORNL's isotopes program grew steadily throughout the 1950s. The Graphite Reactor steadily expanded its menu of isotopes, and a cluster of radiochemical processing facilities sprang up to extract the new elements from the irradiated materials that spawned them. ORNL was the western world's only source of californium-252, a powerful isotope used widely in cancer therapy. In an early example of what would, three decades later, be called technology transfer, Abbott Laboratories built a radiopharmaceutical plant in Oak Ridge to be near its isotope source.

Within ORNL itself, isotopes found eager customers in the growing ranks of Laboratory biologists, who used radioactive tracers, or "tags," to study the chemistry of life. One key finding, in 1956, was the functioning of messenger RNA within the nuclei of cells. Although less famous than its cousin DNA, messenger RNA is no less important: It "reads" DNA's genetic code and turns itself into a template for mass-producing proteins, in something of the way a photographic negative allows many duplicate pictures to be printed.

Other pioneering biological work focused on the health effects of radiation. Because of the genetic and structural similarities between mice and humans, ORNL scientists demonstrated that it was possible to use experiments with mice to estimate the effects of radiation doses on humans. Based in ORNL's "Mouse House"—a facility inhabited by hundreds of thousands of carefully bred mice—this work was instrumental in establishing radiation dose limits for workers worldwide. And in a pioneering twist on one symptom of radiation sickness, ORNL biologists used high radiation doses to suppress the immune systems of mice, then performed the world's first successful transplants of bone marrow.

During a half-century career devoted to nuclear technology, Don Trauger witnessed the ascent—and sometimes the crash—of many nuclear projects.



IT'S A BIRD, IT'S A PLANE, IT'S A...REACTOR?!

Even before World War II, the U.S. Navy was eyeing nuclear energy as a power source for long-range submarines. After the war, the Air Force, too, focused on a nuclear-powered dream machine: a bomber capable of remaining aloft for weeks at a stretch. In 1949 the AEC authorized ORNL to design its reactor power plant.

The nuclear plane posed two formidable challenges, recalls engineer Don Trauger, who marked his 50th year of Oak Ridge work in 1992: Could a reactor manage to loft a plane laden with bombs, crew, and—mainly—itself and its shielding? And given the impractical weight of conventional shielding—7 feet of concrete—could the crew survive the radiation exposure?

To study the shielding problem, two reactors were built, says Trauger. Beginning in 1950, samples of various shielding materials and thicknesses were bombarded with radiation in ORNL's new Bulk Shielding Reactor. To explore the airborne reactor's shielding design when aloft and removed from neutrons reflected by Earth, ORNL built an unshielded reactor and hoisted it, by cables slung between steel towers, to heights of 200 feet or more.

For propulsion, ORNL engineers adopted a novel design: a high-temperature "fireball" reactor fueled by molten uranium salts. A 1-megawatt model made a 100-hour test run in 1954, witnessed by Captain Hyman Rickover, General James Doolittle, and Admiral Lewis Strauss, head of the AEC. Next step: a full-scale, 60-megawatt reactor, which Trauger was to operate. "It was called a fireball," Trauger says, "and it was. It was to run red hot."

Before the full-scale reactor could be built, the nuclear plane—freighted with technical, financial, and political baggage—was grounded in favor of ballistic missiles. "Fortunately, it was never completed," says Trauger. "The nuclear aircraft was a big, difficult, complex system that presented unacceptable hazards to friend as well as foe.

"All we had to do was get it into the air over enemy territory," he laughs. "They'd dare not shoot it down."

The AEC scrapped the program in 1957. But the pie-in-the-sky idea laid down-to-earth foundations in reactor fuels, materials, computing, and other areas still being built on today.

THE SIXTIES

New Frontiers

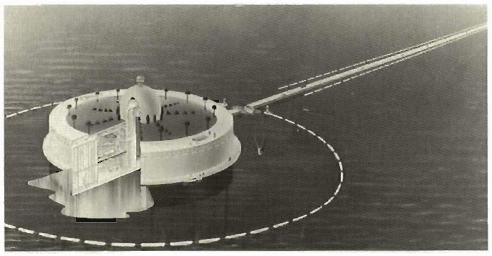
Loud music and *Silent Spring*. Civil rights and civil defense, fallout and sit-ins. "Strangers in the Night" and *Dr. Strangelove*. Free love and costly lessons. Camelot and Cambodia. "Blue Christmas" and Agent Orange. The Great Society and One Small Step. "I Have a Dream" but the dream becomes nightmare: John Kennedy and Lee Harvey Oswald, Martin Luther King and James Earl Ray, Robert Kennedy and Sirhan Sirhan.

In hindsight, at least, it is not surprising that the 1960s, which toppled many an ivory tower, should jostle the nuclear foundations of ORNL.

In the tradition of the 1950s' Atoms for Peace initiative, the early '60s saw the rise of an ambitious new ORNL idea about the place of nuclear power in the world. That place was defined by sand and sea, where ocean met desert: Mammoth nuclear-powered desalination plants could coax fresh water from one, food from the other, figured the Laboratory, with electricity thrown in for good measure. The goal, according to ORNL director Alvin Weinberg, was nothing short of "making the desert bloom with nuclear energy."

The idea won the backing of John F. Kennedy and Lyndon B. Johnson. Nuplexes, as the nuclear-powered desalination complexes were dubbed by the media, were planned for Israel, India, Puerto Rico, Mexico, and the Soviet Union. By late in the decade, though, nuclear power was facing tough times; construction costs were up, public confidence down, and Water for Peace quickly dried up.

Like the nuplex, the Laboratory's molten-salt reactor program faced both boom and bust times. The molten-salt reactor was an electricity-oriented version of the design tested for the Air Force's ill-fated nuclear plane, with the added benefit of breeding fuel for other reactors as it produced power. That feature looked essential, since scores of reactors were now being bought and the world's known reserves of uranium seemed quite limited. A small molten-salt reactor operated successfully at ORNL in 1966, and a larger one from 1968 to 1969, but by this time the AEC was leaning heavily toward a solid-fuel breeder, cooled by liquid sodium metal. For the solid-fuel breeder, designed by Argonne National Lab, ORNL studied coolant flow and temperatures and evaluated materials for the reactor's heat exchangers and steam generators.

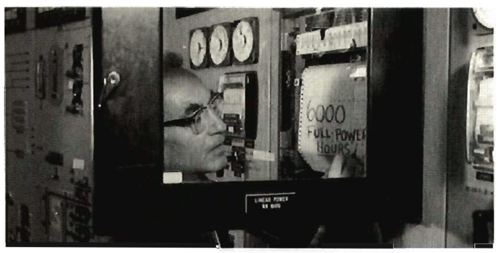


Wellsprings of water and power, offshore nuclear-powered desalination plants—called "nuplexes"—were planned for sea-coasts in the Middle East, the Soviet Union, even thirsty southern California.

Beginning in the late '50s, ORNL began conducting R&D on high-temperature gas-cooled reactors. This work, which continues today with ORNL as the lead laboratory, has included development and testing of the reactor's graphite core structure and ceramic-coated particle fuel, the key components that determine the reactor's exceptional safety and high fuel efficiency. The program, which has also included development of technology for components such as prestressed concrete pressure vessels, has long been characterized by close cooperation with industry, utilities, and other nations, including Japan, Germany, and other European countries.

As the ranks of reactors grew, so grew public worries about them, and nuclear safety became a fast-growing research field at ORNL. One program, begun in the 1940s, came into its own during this period: A group of researchers gathered and analyzed extensive data about nuclear reactors and their operation, logging and sharing information about problems with the new power source. Their journal, *Nuclear Safety,* is still the preeminent source in its field. At a more nuts-and-bolts level, engineers and metallurgists began testing the limits of reactor pressure vessels—the mammoth stainless-steel crucibles that contained the nuclear fire of commercial reactors—subjecting them to brutal extremes of heat, pressure, and cold to test their, well, *metal*.

Perhaps nuclear energy's brightest spots at ORNL in the 1960s were two reactors, one big and one small: the High Flux Isotope Reactor and the Health Physics Research Reactor. The Health Physics Research Reactor, completed in 1962, had a core about the size and shape of a kitchen Crockpot. First hoisted up a 1,500-foot tower in Nevada, like a higher-flying version of ORNL's Tower Shielding reactor, it came the following year to Oak Ridge. Once settled here, it spent the next quarter century yielding radiation-exposure data that proved instrumental in refining occupational dose limits, designing dosimeters for nuclear workers, and devising shields for power plants and space craft.



Long hours, short life: ORNL's Molten Salt Reactor Experiment—a promising concept that later fell by the wayside—had a successful 1967 test run, certified by Lab Director Alvin Weinberg.

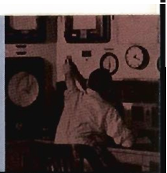
At the other end of the spectrum was the High Flux Isotope Reactor, completed in 1965. It was HFIR ("HI-fur") that made up, finally and spectacularly, for ORNL's loss of the Materials Testing Reactor to Idaho a decade and a half earlier. With the world's most intense neutron flow (flux), HFIR quickly gained a reputation both as a powerful research tool and as a superb production plant for exotic isotopes such as berkelium, californium, einsteinium, and fermium.

TELLING TIME

Five Decades of Life and Science

World's first chain reaction, at Chicago

1942



1943

ORNL's Graphite Reactor "goes critical"

Korean War begins

Bulk Shielding Reactor completed

Oak Ridge School of Reactor Technology established

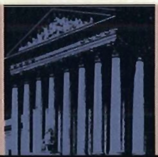
1950

86-inch cyclotron completed, with world's most intense proton beams

RNA's chemical components identified, showing close link to DNA

1953

ORACLE, then world's most powerful computer, installed at ORNL



Supreme Court bans school desegregation in Brown vs. Board of Education case

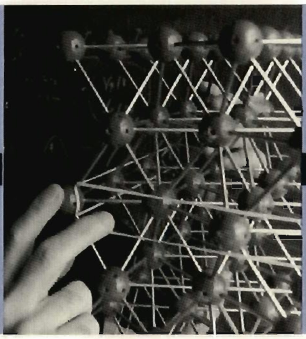
1954

ORNL's experimental aircraft reac[tor] tested

Ground broken for nation's first co[m]mercial nuclear power plant, near Pittsburgh

Development begins on isotope heat sources to power space satellites

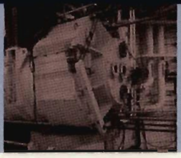
1961



ORNL discovers phenomenon of ion channeling in crystalline solids—key to semiconductors

1962

Oak Ridge Isochronous Cyclotron completed

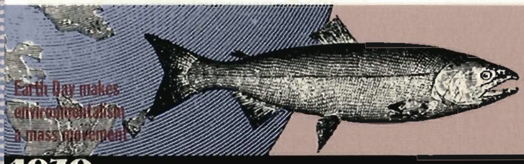


1960s

Martin Luther King, Jr., tells 200,000 in nation's capital, "I have a dream...."

1963

President John F. Kennedy assassinated

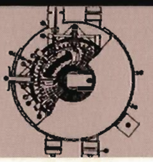


Earth Day makes environmentalism a mass movement

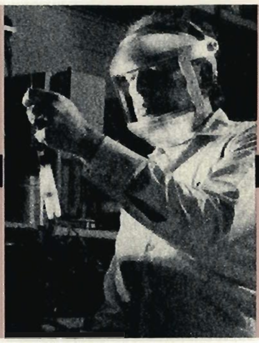
1970

ORNL studies environmental impact of nuclear-plant cooling water on rivers

1971



ORMAK, experimental fusion tokamak, begins research



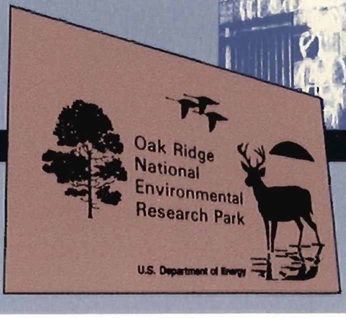
1972

World's first successful freezing, thawing, and implantation of mouse embryos

1980s

1980

ORNL opens three user facilities: accelerator lab, neutron research facilities, environmental research park

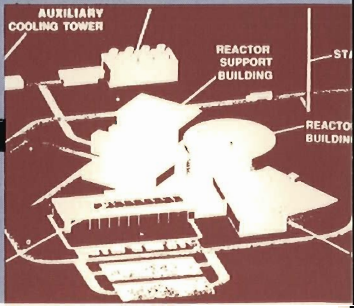


1982

AIDS cases surge

Union Carbide, operating contractor since 1948, announces withdrawal

ORNL begins helping developing nations assess energy technologies and policies



1940s

1945

Atomic bombs dropped on Japan

1946

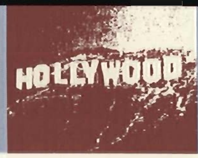
Baby boom begins

U.S. Navy Captain Hyman Rickover studies reactor technology at ORNL

First isotope shipment to cancer hospital

1947

House Un-American Activities Committee black-lists Hollywood communist sympathizers



1948

Biology program established, using mice to estimate radiation effects

Union Carbide becomes operating contractor

UNION CARBIDE

1955

ORNL "swimming pool" reactor showcased at UN atoms-for-peace conference

First nuclear-powered submarine, *Nautilus*, undergoes sea trials

1956

ORNL biologists discover function of messenger RNA

First experimental bone-marrow transplants in mice performed at Mouse House

1950s

1957

First ORNL fusion-energy experiment begins

Sputnik launches space race

1958

Alvin Weinberg appointed ORNL director after 13 years as research director

Relationship between intensity of radiation doses and their effects discovered

Oak Ridge Research Reactor begins 30 years of research and isotope production

1964

Water for Peace, nuclear desalination concept, featured at UN conference

1965

High-Flux Isotope Reactor and Molten Salt Reactor begin operation

ORNL-Univ. of Tenn. graduate program in biomedical science established

U.S. escalates Vietnam war

1966

Oak Ridge Electron Linear Accelerator completed

1969

Apollo moon landing; ORNL-designed equipment collects rock samples

1970s

1973

U.S. troops leave Vietnam

Arab oil embargo causes gas lines, prompts flurry of energy-related R&D

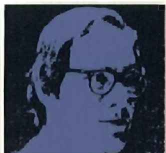
Alvin Weinberg becomes White House science advisor

The Washington Post FINAL

Nixon Resigns

Ford Assumes Presidency Today

1974



Herman Postma becomes ORNL director

President Nixon resigns in wake of Watergate scandal

1977

Construction begins on Large Coil Test Facility for superconducting fusion magnets

1979

Three Mile Island nuclear-plant accident; ORNL helps with analysis and cleanup

MARTIN MARIETTA

1984

Martin Marietta Energy Systems, Inc., assumes ORNL operating contract

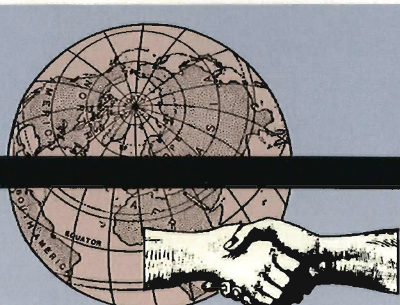
Planning begins for Advanced Neutron Source, next-generation research reactor

Ecological and Physical Sciences Study Center opens, attracting thousands of students per year

1987

High-Temperature Materials Laboratory opens as user facility

Five ORNL research reactors shut down for safety reviews



1988

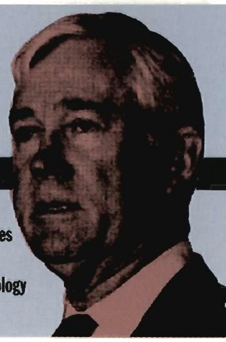
Alvin Trivelpiece appointed director

Center for Global Environmental Studies created

Berlin Wall topples

High-Flux Isotope Reactor resumes operation

National Competitiveness Technology Act passed



Shooting for the moon, in 1966 ORNL built this isotope-powered generator for the lunar probe Surveyor. The bowling-ball sized generator packed the punch of 60 conventional automobile batteries.

Besides shedding pure, academic light on nuclear reactions, these isotopes earned their keep in the pragmatic world: Some were employed to seek oil and minerals; others to seek cancer, and still others to destroy it—in tumor-killing needles, for example, made of the potent neutron source californium-252. For materials researchers, HFIR's neutron beams represented a major step beyond the Graphite Reactor, where the field of neutron research began. Coupled with sophisticated new detectors and other instruments developed by the Lab to measure how they were scattered by materials, HFIR's intense neutron beams revealed previously unknown (and otherwise unknowable) details about the structure and properties of plastics, metals, ceramics, magnetic materials, and components of living cells.

Digging In With the Iron Curtain dividing Berlin, nuclear missiles steaming toward Cuba, and Nikita Kruschev pounding his shoe at the United Nations, temperatures in the Cold War reached record lows during the early '60s. In 1964, as American adults dug backyard bomb shelters and schoolchildren dove beneath desks, ORNL began a serious study of civil defense, reasoning that the less vulnerable Americans were to nuclear attack, the less likely attack would be. Drawing on the Lab's expertise in shielding and radiation detection, the program evaluated protective measures such as civilian evacuation plans, underground networks of tunnels, and the effects of fallout on food crops and other vegetation—ecological work that would later bear fruit, so to speak, in the broader environmental programs of the '70s and beyond.

Biology at the Nucleus The 1961 publication of Rachel Carson's book *Silent Spring* signalled the beginnings of a new public awareness of the environment ... and the impact of human development on it. Concerns about chemical pollution gradually spawned new biochemical research, which built on the Lab's earlier studies of radiation effects.

Researchers focused increasingly on the cell nucleus—specifically, the genetic material that appeared most crucial to life and most vulnerable to damage. Using high-speed centrifuges first developed to enrich uranium for the Manhattan Project, ORNL biologists separated large-scale quantities of messenger RNA, whose protein-building function the Lab had deduced in 1956. The centrifuges were also adapted to separate other materials, including blood, urine, and plasma from leukemia victims (leading to the Lab's discovery of virus-like particles within the leukemic plasma), and vaccines, which were purified in commercial versions of the research centrifuges. In an extension of the radiation-effects work begun years earlier, the Lab's biologists experimented with mice to investigate the health effects of chemicals such as pesticides, gasoline fumes, drugs, and tobacco.

HFIR revealed otherwise-unknowable details about the structure of plastics, metals, ceramics, and magnetic materials.

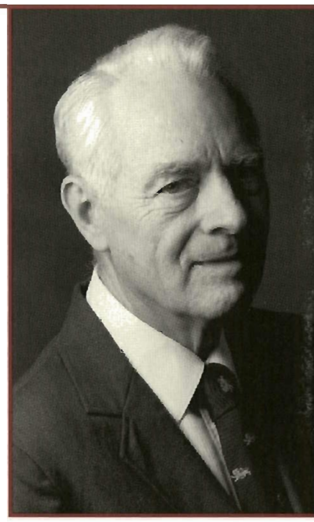
By 1965, the growing international reputation of the Biology Division led to the creation of a graduate program in biomedical science at Oak Ridge, a joint venture of ORNL and the nearby University of Tennessee. Over the next three decades, this program would serve as a graduate and postgraduate training ground for hundreds of the nation's most promising biomedical researchers.

Insighting a Revolution One of the most important findings to emerge from ORNL in the 1960s was almost accidental. To explore the fundamental physics of radiation damage—a problem dating back to the Lab's Manhattan Project days—two scientists laboriously programmed an early IBM computer to simulate the billiard-ball physics of charged atoms careening into crystalline metals. One day the computer kept running and wouldn't stop: A particle had entered a crystal and just kept going. The reason, they deduced, was that the particle had entered a tunnel, or channel, within the crystal's orderly stack of atoms. This insight paved the way, eventually, for precisely controlled implantation of electrically active impurities within crystals—the basis for the semiconductor chips that created the electronics revolution.

In the end, despite growth and progress in fields such as physics and biology, ORNL finished the 1960s on a gloomy note, one that bore more than a passing resemblance to the postwar letdown of the late forties: The AEC cut the Oak Ridge breeder-reactor program by two-thirds and killed plans for a powerful new particle accelerator; over the next five years, the Lab's staff plummeted by 30 percent, from 5,500 to 3,800. Once again a changing world would require changes at ORNL. "Our vast scientific apparatus is deployed against scientific problems," lamented director Weinberg at one point, "yet what bedevils us are strongly social problems."

Still, given the buffeting other institutions weathered in the '60s, ORNL fared remarkably well. Camelot and the ivory tower may have fallen and the nuclear dome been shaken, but, deep down, ORNL's scientific foundations held firm.

Undeterred by weightlessness, space-project engineer Art Fraas felt his ardor for research cooled by the icy waters of Lake Erie.



SHOOTING FOR THE MOON

President John F. Kennedy's pledge to put Americans on the moon in the 1960s entered ORNL in the race for space. The National Aeronautics and Space Administration asked ORNL to predict how astronauts would be affected by Earth's Van Allen radiation belts and the sun's radiation. To find out, Oak Ridge biologists sent bacteria and blood samples into space and exposed small animals to radiation. To develop shielding for the Apollo crews, researchers recycled the Lab's Tower Shielding Facility, which had hoisted shielding experiments aloft for the previous decade's nuclear-plane project.

But the Apollo program was only one leg of the space race. ORNL helped carry the baton in other legs, too, recalls retired engineer Art Fraas.

Fraas led the design of a reactor to power satellites and manned outposts such as space stations. One key challenge he and his colleagues faced was finding a way, without gravity, to round up the reactor's working fluid—the liquid that would be heated into turbine-spinning vapor—after it recondensed. Fraas figured that with tapered condenser tubes, surface tension just might do the trick: The fluid might migrate toward the narrower ends of the tubes, much as a rubber band might tighten its way toward the tip of a slippery cone. A set of free-fall tests looked promising, but a definitive answer would require a longer zero-gravity experiment.

In 1965, Fraas found the needed weightless condition in an Air Force KC-135, a plane whose roller-coaster-like maneuvers let astronauts cut their zero-G teeth for a half-minute at a stretch. Fraas hoped to go along for the ride until he learned the prerequisite for the flight: a practice parachute jump, from 10,000 feet, into the frigid March waters of Lake Erie—just in case the high-stress maneuver "ripped the wings off the plane," he explains. An Air Force technician tended the successful experiment instead.

The farthest-reaching products of ORNL's space program have been its radioisotope power sources for space probes. These generators are fabricated from isotopes and sealed in crash-resistant capsules made by ORNL; their radioactive decay produces heat, which is converted to electricity to power instruments, cameras, and transmitters. Simple and reliable, power sources like these are still, a quarter-century after their development, energizing deep-space probes such as Voyager and Magellan, which keep going and going....

THE SEVENTIES

Energy Urgency

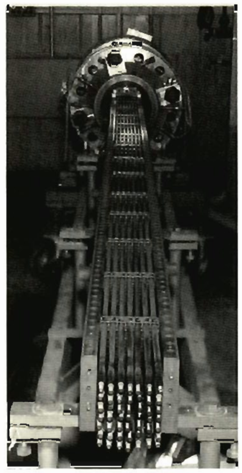
The Brady Bunch and the Watergate Five. Presidential privilege, pardon, and peanuts. Earth Day and the EPA. Peace with honor, Big Mac with fries. Bell bottoms and halter tops. Walking on Earth Shoes. Running on empty.

Within the realm of science and energy, the defining events of the 1970s were oil shortages: first in 1973, then again in 1977. Waiting in long lines for short supplies, many Americans realized for the first time how central a role energy plays in the good life ... and how vulnerable some forms of energy are to political vagaries. Thus began, after the Mideast oil embargo of 1973-74, a rush to diversify America's energy base and to reduce U.S. dependence on imported oil.

Even before the embargo, some steps toward diversification had already been taken. In 1970, Congress told the AEC to broaden its nuclear horizons to include other energy sources. In 1974, the AEC split into two agencies: the Nuclear Regulatory Commission, to oversee nuclear power, and the Energy Research and Development Administration, to cultivate new energy sources and technologies. Finally, in 1977, a bitter winter and a heating-oil shortage moved President Jimmy Carter to proclaim energy crises "the moral equivalent of war" and to retool ERDA into the cabinet-level Department of Energy.

ORNL, for its part, had already foreseen the future of energy. In a series of planning sessions in the early '70s, Laboratory staff identified a number of looming issues and opportunities, including recycling, conservation, synthetic fuels, and solar power.

Environmental Impacts The first Earth Day, held in April 1970, catapulted environmentalism from society's fringes to its mainstream. If the 1961 book *Silent Spring* represented the seed-sowing of the environmental movement, Earth Day symbolized the first big harvest, followed swiftly by broad environmental laws.



For nuclear reactors, cooling was a hot topic in the '70s. This simulated fuel-rod bundle was instrumented to show how fuel would be affected by a loss of coolant.

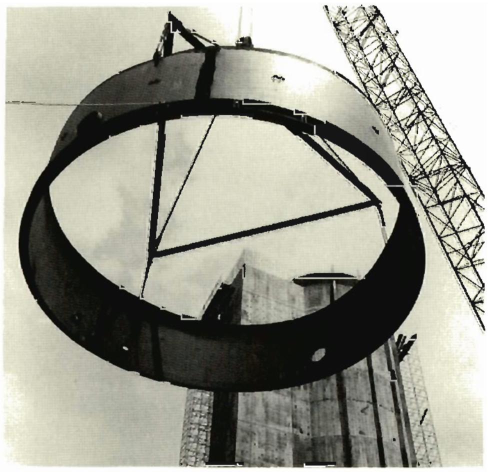
Fittingly, or ironically—perhaps both—ORNL galloped into the environmental field on the broad back of nuclear power. In 1971 a federal court issued a decision that would reshape, literally, nuclear power: In resolving a lawsuit opposing construction of the Calvert Cliffs nuclear plant in Maryland, the court ordered the AEC to detail the environmental impacts of every nuclear power plant in operation, under construction, or on the drawing board. Charged with completing 92 environmental impact statements by 1972, the AEC looked to Oak Ridge for help.

One key issue was how aquatic life would be affected by hot water discharged from nuclear plants into the nearby rivers. To find the answer, ORNL built an aquatic ecology lab, where fish were subjected to a range of water temperatures. After studies showed that high temperatures lowered the survival rates of fish and their eggs, the government imposed strict temperature limits on nuclear plant discharges. As a result, Calvert Cliffs and dozens of other plants installed the massive cooling towers whose shape is visually synonymous with nuclear power.

Other Nuclear Challenges Technically, too, the 1970s were a challenging decade for nuclear power. In the interests of safety, ORNL found itself complicating life for the very technology it had helped create. In the early 1970s, ORNL wrote nearly 100 interim safety standards for the AEC, addressing such needs as earthquake protection, rugged fuel-shipping casks, and emergency cooling systems.

Emergency cooling proved the hottest issue. In 1972 the AEC held a series of public hearings on the topic. Nuclear-power opponents vigorously challenged nuclear engineers—an unnerving new experience for some scientists. The hearings produced reams of testimony—and stiffer safety criteria.

ORNL Director Alvin Weinberg summed up the dilemma this way: "Nuclear people have made a Faustian contract with society," he wrote. "We offer...[a] miraculous, inexhaustible energy source; but this energy source at the same time is tainted with potential side effects that if uncontrolled, could spell disaster."

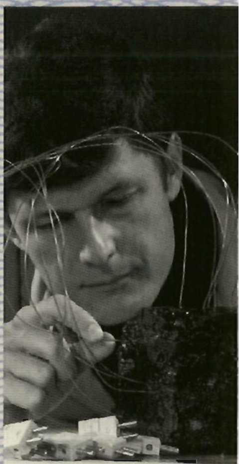


Tower of power, the Holifield Heavy Ion Research Facility, here under construction in 1977, would become the world's most powerful heavy-ion accelerator.

The prescience of Weinberg's words was underscored in 1979, when a reactor at the Three Mile Island nuclear plant overheated and badly damaged its core. ORNL played a key role in analyzing the accident and assessing the core damage; Laboratory scientists also helped prevent the release of radioactively contaminated gases and devised ways to decontaminate thousands of gallons of emergency coolant. Although little contamination escaped from the plant—testimony to the multiple layers of safety that ORNL's earlier work had helped establish—the highly publicized accident reinforced public fears about nuclear power.

Finally, in a blow to the future of nuclear power (and ORNL nuclear programs), the Clinch River Breeder Reactor ground to a halt at the end of the decade. The project—a joint venture of DOE, the Tennessee Valley Authority, and the nuclear industry—was plagued by spiraling costs, slow progress, and concerns over terrorist diversion of the plutonium it would breed.

Small but wiry, this chunk of coal—connected to instruments probing its internal heat-transfer properties—was a piece of ORNL's ambitious coal program in the mid '70s.



Less Is More Conservation, meanwhile, thrived on the decade's energy austerity. A barrel saved is a barrel, well, *saved*—in this case, from importation. Recognizing the major role that heating and cooling buildings plays in energy consumption—one-fourth of the U.S. total—ORNL led the development of insulation standards that were later adopted by federal agencies, mobile-home makers, and trade associations. ORNL studies also guided utility-sponsored efforts to retrofit existing homes with better insulation, storm windows, and heat pumps.

On the home front, ORNL studied the energy consumption of refrigerators, furnaces, water heaters, ovens, and heat pumps. The program contributed to efficiency standards and improved appliances, including heat-pump water heaters and better refrigerators. Within a decade, most U.S. homes would have at least one appliance made more efficient by the Lab's conservation research.

The Coal War The U.S. contains nearly half the world's coal. By 1975, ERDA had decided to tap this abundant resource. The goal: a million barrels of synthetic oil per day by 1985.

ORNL undertook fundamental studies of the structure, properties, and chemistry of coal, one of nature's most complex and byzantine minerals. Researchers began developing alloys and ceramics equal to the heat and corrosion expected in synfuel plants; they also designed high-efficiency furnaces, coal-processing techniques, and waste treatments to help coal come clean.

And, in the tradition of earlier research on radiation's health effects, ORNL launched studies of the chemistry and physics of coal liquids, their biological effects, and possible harm to the environment. At the Mouse House, the mutagenic (gene-changing) properties of synfuels proved worrisome.

Fusion's Second Era As if to confirm the adage that "a rising tide lifts all boats," even fusion—a distant prospect at best—benefited from the decade's energy urgency. After the 1960s' slow fusion progress, the '70s saw a resurgence of hope. Soviet scientists had recently managed to confine fusion's elusive plasma in a device called a tokamak. By 1971, ORNL's tokamak, ORMAK, began its own series of plasma experiments. After two years of encouraging results, ORMAK was enlarged and renamed ORMAK II; Weinberg hoped it would lead, in turn, to ORMAK III, "which might be the fusion equivalent of the 1942 [fission] experiment at Stagg Field."

ORMAK III was never built, but other devices were built for further plasma studies. So were systems to fuel them (by shooting frozen hydrogen pellets into the test chambers) and to heat their plasmas (by zapping them with microwaves and beams of hydrogen particles). With near-symbolic aptness, fission pioneer Alvin Weinberg was succeeded in 1974 by Herman Postma, a fusion physicist who would head the Laboratory for the next 14 years.

In 1977, with an eye to future fusion reactors, ORNL began building a facility to test large, superconducting electromagnets. The six test magnets, measuring 20 feet high, would be nearly half the size of those that might someday be needed for power-producing reactors. In a program marked by strong international cooperation, three magnets would be built by U.S. manufacturers, three by foreign partners—Japan, Switzerland, and the European Community. Once sealed in a vacuum tank, the magnets would be supercooled by liquid helium; their molecules would become virtually motionless, making the magnets free of efficiency-robbing electrical resistance. The facility would prove to be one of ORNL's most ambitious and successful fusion programs.

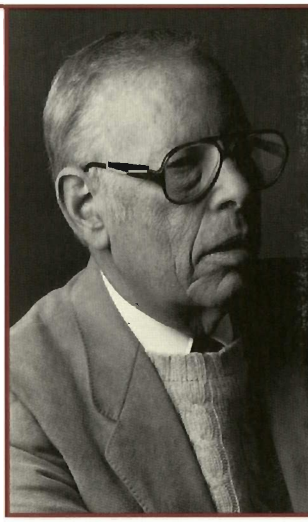
Within a decade, most U.S. homes would have at least one appliance made more efficient by ORNL research.

Basically Speaking While the Lab, like the nation, focused strongly on energy during the 1970s, ORNL's basic research scientists were reaping the benefits of sophisticated facilities acquired over the past decade. Beginning in the early 1960s, the High Flux Isotope Reactor established Oak Ridge as a world leader in isotope production and neutron research. Two powerful physics facilities completed in the 1960s—the Oak Ridge Isochronous Cyclotron (ORIC) and the Oak Ridge Electron Linear Accelerator (ORELA)—allowed new research into heavy elements and ions. A university consortium linked an on-line isotope separator to ORIC's beams, yielding new radioisotopes for medical and industrial use, heavy nuclei such as those in stars, and other exotic nuclear phenomena.

In ORELA, electrons were fired through a 75-foot tube at a water-cooled tantalum target, where the collision produced neutron bursts 10 times as intense as those from any other linear accelerator. (In 1990, scientists would use ORELA to confirm the existence of separate positive and negative electrical charges—quarks—within the neutron.) In 1975, work began on a still more powerful accelerator, one that would become a world center for heavy-ion research in the 1980s. And, building on the previous decade's insights into crystal structure, ORNL physicists became adept at rearranging the surface and near-surface atoms in materials—a research feat that would lead to high-efficiency solar cells, diamond-hard optical coatings, and longer-lasting artificial joints.

Although it was the 1960s that brought radical changes to the nation, it was the 1970s—the nuclear-bashing, tree-hugging, energy-starved '70s—that transformed ORNL from an atomic laboratory into a complex R&D center, one embracing an array of interrelated energy, environmental, and scientific challenges.

Frost biologist Peter Mazur married cryogenics with embryology —and the union was blessed with issue.



LIFE ON ICE

In 1972, ORNL biologist Peter Mazur and two colleagues announced a startling breakthrough: They had deep-frozen mouse embryos, storing them for days in liquid nitrogen (at -196 degrees Celcius), then thawing and implanting them in a surrogate mother. The cover of Science *magazine showed the experiment's outcome: healthy mouse pups, frost-free.*

In two weeks of experimentation, the team had accomplished what other cryobiologists (literally, "frost biologists") had sought for two decades. "It was not due to any brilliance on our part," recollects Mazur, "but because the principles of cryobiology were well-enough established that we thought we knew what we were doing."

The technique was soon adopted by the livestock industry as a way of sharing the genetic wealth of superior cattle: Embryos are now routinely frozen in the United States, then air-expressed to waiting cows in, say, eastern Europe. "If you make the cow superovulate, you can get up to 25 embryos from a single ovulation," Mazur notes, multiplying a prize cow's reproductive potential by a factor of dozens or even hundreds.

Embryo freezing remained low-profile until the 1980s, when it made its way to human fertility clinics. The technique was made famous—or infamous—by two thorny legal cases: An Australian couple died and a Tennessee couple divorced, derailing the original plans for their embryos. Theoretically, says Mazur, the embryos in such cases could remain in limbo—biologically and ethically—for hundreds or even thousands of years.

Despite the dilemmas surrounding human embryo freezing, Mazur is bullish on cryobiology's future uses: preserving endangered animal species—for example, implanting horses with embryos from rare zebras—and keeping research mice or fruit flies on inexpensive ice, protected from, say, laboratory fires or study-skewing mutations called "genetic drift." Eventually, the frosty technique could also be adapted to preserve transplant-bound human organs while their host is gradually introduced to its new tissues.

Two decades after making news with the cool technique, Mazur still has a warm spot in his heart for it.

The Eighties

Open for Business

Donald Trump and The Deal. Yuppie success and homelessness. Supply/demand and Afghanistan. Qaddafi and Khomeini; Madonna and Michael; Gorby and the Gipper. MTV and HIV and Pam Am flight 103. Read My Lips: Just Do It but Just Say No. Just the fax, and ET phone home. Berlin Wall comes a-tumblin' down.

It's early yet to formulate judgments on ORNL's 1980s, to assign the orderings and meanings that add flesh and nerve to a history's skeleton of fact. But already some things stand out clearly.

No less surely than social turmoil influenced ORNL's 1960s and energy concerns shaped its '70s, the "Reagan Revolution" guided much of the '80s—and sometimes set sharply different courses. Synfuels (and ORNL's coal program) were out; so was "shivering in the dark," according to President Reagan, along with most government funding for solar and geothermal research. Energy independence was out: By the end of the decade, imports would supply nearly half of America's oil. Even the Department of Energy itself was out, condemned (sporadically and unsuccessfully) to administrative execution because, the president said, it had "never produced one barrel of oil."

What was in was "Star Wars"—the Strategic Defense Initiative—for whose missile-killing systems ORNL developed rugged, high-precision optical windows, mirrors, and high-energy particle beams. Also in was the free market, which, if given rein, would balance energy supply and demand. So were nuclear power (theoretically, if not fiscally) and basic research, the long-range, high-risk kind that corporate America couldn't afford to gamble on in the way ORNL had been gambling—with the calculation born of expertise and strategic thinking—for four decades.

Less Is Still More On first glance, the Lab's energy-conservation work might have seemed doomed in the 1980s, destined for the free-market chopping block. In the end, though, ORNL's strong focus on high-tech materials—tough, heat-resistant ceramics for advanced auto and truck engines, especially—gave it the long-range, high-risk orientation needed to pass White House muster. In addition, the program's responsiveness to the research needs of turbine- and diesel-engine manufacturers won surprisingly strong support from the industrial sector.

The program's heritage was nuclear: materials development for reactors in the '50s. The materials work survived nuclear power's hard times by shifting to industrial energy efficiency in the 1970s. Now, the transition to transportation-oriented ceramics development represented yet another new lease on life. By 1987 the program had become one of the Laboratory's largest; it moved into a sophisticated new R&D complex, the High Temperature Materials Laboratory, where ORNL scientists work side-by-side with industry researchers to develop and test advanced ceramics and alloys.

Other conservation work—development of high-efficiency heat pumps and joint R&D with the building-insulation industry—also survived and grew during the 1980s. After the initial uncertainties, funding for ORNL's conservation program more than doubled during the Reagan era.

Opening Doors The success of the Lab's materials program underscored a hallmark of the 1980s at ORNL, one that was more a matter of style than of substance: *How* the Lab researched began to matter almost as much as *what* the Lab researched. Programs and facilities throughout the Lab began opening their doors to scientists and engineers from universities and industry. In the first year of the decade, three major new "user facilities" opened:

▸ The Holifield Heavy Ion Research Facility, with its 25-million-volt electrostatic accelerator, offered twice the power of similar machines, plus an adjoining cyclotron to serve as a post-accelerator. With the world's widest range of heavy ion species and energies, the Holifield facility became a mecca for western-world scientists, averaging hundreds of guest researchers each year. It also served as a model for other specialized facilities geared toward outside researchers.

▸ To capitalize on the intense neutron beams of the High Flux Isotope Reactor, the Laboratory established the National Center for Small-Angle Scattering Research, the nation's first neutron-research complex to operate as a user facility. By detecting how neutrons are deflected, or scattered, by samples, the center allowed visiting researchers from universities and corporations (including DuPont, Exxon, and IBM) to probe the structure and properties of a wealth of materials: tough new plastics made of tightly ordered molecular chains, radiation-resistant alloys for fusion reactors, DNA and other tiny structures within cells.

▸ At the other end of the technological spectrum were the research tools offered by a third new user facility: trees and grass, water and rocks, dirt and bugs. The 12,400 acres of the National Environmental Research Park offered researchers a living laboratory for studies of acid rain, animal populations, pollutant migration through the ecosystem, and waste-digesting bacteria.

By 1990, the Lab was home to a dozen user facilities, ranging from accelerators and ceramics labs to a large climate-simulation chamber that could compress weeks of insulation-battering

Cleaning up ORNL's own backyard became a priority during the 1980s, commanding unprecedented resources and attention. The Lab built these new underground silos to isolate low-level radioactive waste.

On the surface of things, ORNL physicists in the 1980s harnessed accelerators and lasers to create high-tech materials, ranging from diamond-hard optical coatings to better artificial joints.

weather into the space of days. In 1991 these facilities would attract 3,600 guest researchers to ORNL; 30 percent of them were industry scientists, a sixfold increase since 1980.

Prime time for nuclear safety: Video inspection of the High Flux Isotope Reactor in 1987 helped ensure the soundness of the reactor's key components after a quarter-century of operation.

In addition to user facilities, ORNL pioneered other ways to transfer the benefits of its work into the private sector during the 1980s: Cooperative R&D agreements, called CRADAs, allow corporations to work directly with ORNL experts to solve specific problems or develop proprietary technologies or processes. Invention-licensing policies allow companies to secure marketing rights to ORNL developments. Royalty-sharing provisions also give ORNL inventors a share of the proceeds if their invention meets a market need.

And in the open-door program with perhaps the longest-range focus of all, ORNL dramatically expanded its links with regional and national educational institutions—including the University of Tennessee, historically black colleges, and other schools—offering innovative programs for students at every level from kindergarten through postdoctoral research. In 1984, for example, the Lab created the Ecological and Physical Sciences Study Center, a hands-on, outdoor classroom where thousands of students each year perform chemical "magic," ferret out animal signs, and acquire a literal feel for natural selection—the skins and skulls, teeth and claws that fit various species into their ecological niches. Fittingly, when Alvin Trivelpiece became ORNL's director in 1989, education became one of his top priorities. With experience in senior posts at DOE and the American Association for the Advancement of Science, Trivelpiece was the Lab's first "outside" director—and an apt symbol of newly opened doors.

Cleaning Up the Backyard One of the most painful and costly tasks of the decade—for ORNL as for many other DOE facilities—was coming to environmental terms with decades of radioactive and chemical wastes. Groundwater beneath the Lab had been contaminated by leaks from burial trenches and aging pipes. Old radwaste tanks had to be emptied and decontaminated; leaking chemical drains had to be repaired or replaced. By some reckonings, cleaning up ORNL's backyard could take three decades and hundreds of millions of dollars.

Similarly, ORNL spent months and millions in the 1980s assessing the operating procedures and safety systems of its five research reactors: the High Flux Isotope Reactor, Bulk Shielding Reactor, Tower Shielding Facility, Oak Ridge Research Reactor, and Health Physics Research Reactor. In 1987, DOE ordered the five reactors idled for detailed safety reviews. In 1989, with the nation's inventory of certain isotopes badly depleted, a refurbished HFIR was restarted, with less power but more safety procedures; the Tower Shielding reactor was later revived as well. It was a far cry from the brash, can-do days of the Graphite Reactor, when researchers yoked a toy generator to the reactor to make the world's first nuclear power: a one-third watt trickle that lit a flashlight bulb. ORNL's reactors had come of age, and a cautious late-middle age, at that.

By 1990, the Lab was home to a dozen user facilities, ranging from particle accelerators to a 12,400-acre "living laboratory."

Amid the setbacks, though, came a ray of hope on the nuclear horizon: In 1984 the Lab began planning an ambitious new research reactor, the Advanced Neutron Source, to begin operation at the turn of the century. With 10 times the neutron intensity of the HFIR—and an equal advantage over HFIR's newer, more sophisticated rival in France—the billion-dollar project aimed to restore the U.S. lead in neutron research and establish itself as the world's finest research reactor.

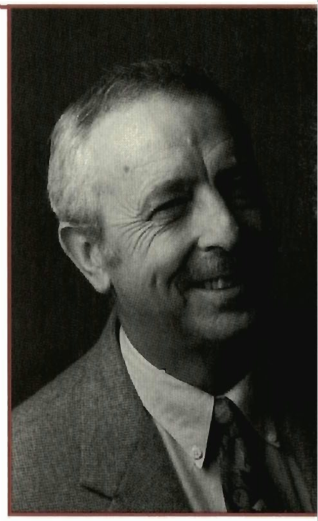
Designer Genes ORNL's studies of the genetic effects of chemicals broadened during the 1980s to include more fundamental research on genetic disorders themselves—the basis for an estimated 4,000 inheritable diseases or medical problems: birth defects, kidney disease, schizophrenia, even some forms of cancer. ORNL biologists began harnessing a powerful new tool for probing genetics disorders: "transgenic" mice, whose genes contain an added fragment of foreign DNA. By knowing a transgene's location and observing the mice that develop from transgenic eggs, researchers are beginning to pinpoint the genes responsible for normal—and abnormal—development of limbs, spine, kidneys, brain, heart.

Similarly, using new techniques of protein engineering, ORNL researchers began exploring the intricate workings of enzymes, the regulators of the complex biochemistry we call life. An enzyme of particular interest is one that regulates photosynthesis. If enzymologists can someday re-engineer the enzyme for higher efficiency, they could boost crop yields, speed reforestation, and slow the buildup of carbon dioxide in Earth's atmosphere.

Thinking Globally As international boundaries shifted and blurred in the 1980s, ORNL's boundaries broadened. Starting in 1982, at the request of the U.S. Agency for International Development, ORNL scientists embarked for some two dozen developing nations to help with energy technology and policy assessments. The assessments help countries identify ways to secure the energy they need for economic growth, while reducing stress on the global environment and world oil market.

In another nod to the global village, in 1989 ORNL established the multidisciplinary Center for Global Environmental Studies. Some problems—greenhouse gases, ozone loss, climate change, species extinctions—know no boundaries.

Shooting for the hip, physicist Jim Williams fired nitrogen atoms into titanium alloy; biomedical companies walked away with tougher artificial joints.



FROM CHIPS TO HIPS

What began as pure research—numbers in a computer model—has ended up, decades later, in artificial joints that replace some 100,000 crumbling hips and knees every year.

In the early 1960s, ORNL physicists had used computers to model the way impurities tunnel into crystalline solids during ion implantation, the blasting of charged atoms into materials. Their research helped pave the way for today's semiconductor chips, whose electrical properties arise from carefully controlled impurities (called dopants) deposited in silicon or other insulators.

In 1980, physicist Jim Williams began seeking new ways to use ion implantation. Ion-implanting even a thin layer near a material's surface, Williams and his colleagues knew, could radically alter the surface properties, imparting hardness, say, or corrosion resistance far beyond that of the base material or dopant.

It was just those properties, in fact—hardness and corrosion resistance—that were needed in materials for artificial joints. The combined stresses of wear and corrosive body fluids take their toll on implants; a titanium-alloy knee could wear out in only a few years, for example, necessitating another painful operation. But working with a materials scientist at the University of Alabama in Birmingham—home to a large medical center—Williams found that implanting the titanium's surface with nitrogen ions made a remarkable difference in its resistance to wear and corrosion. The technology was rapidly adapted for commercial use by Spire Corp., a Boston company specializing in high-tech surfaces for aerospace, electronics, and biomedical components.

By 1993, Spire expects to be ion-treating nearly 50,000 artificial knees a year, plus a similar number of artificial hips (in hip prostheses, ion-treating the cobalt-chromium "ball" makes the metal even harder—but kinder and gentler to the joint's polyethylene "socket").

A decade ago, Jim Williams figured out something that now helps tens of thousands of artificial-joint recipients every year: Sometimes, making things a little harder makes them a lot easier.

A Vision, Still

Conservationist John Muir wasn't talking about ORNL history when he said it, but he might as well have been: "When we try to pick out anything by itself, we find it hitched to everything else in the universe." ¶ On first glance, there's little resemblance between the sprawling ORNL of today and the single-mission radiochemical pilot plant of World War II. A closer inspection and a longer view, though, show otherwise: An early scientific path led here, then branched this way and that; another converged from over yonder. Witness: The Graphite Reactor showed many uses for nuclear energy, both as a scientific probe and as a pusher of submarines and spinner of turbines. And it led to other research reactors, beyond which awaits the Advanced Neutron Source. ¶ But the Graphite Reactor was the trailhead for other paths also, such as explorations of the problems—technological, environmental, and safety—that arose as a whole generation of nuclear reactors began showing their age and imperfection. And the wartime separation of plutonium led to the peacetime extraction of radiochemical exotica, and the development of nuclear medicine. ¶ So it is with every path the Laboratory treads: It probably came from a patch of familiar scientific ground, and sooner or later it's likely to lead some other place worth exploring. ¶ For the next 50 years, the journey begins with genetic research, protein engineering, advanced materials, environmental science, nuclear safety, fusion research. No one can say where it leads. ¶ Hard though it was to see at times, ORNL's half-century of explorations have positioned it to head toward precisely these kinds of urgent challenges. ¶ John Hendrix' vision ended with "the greatest war that ever will be." ¶ ORNL's vision just began there.

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